

and can "see" higher; their disadvantages are that they require larger antennas than the higher frequencies and the lowest sampled height is relatively high. Figure A-3 compares typical performance characteristics at three frequencies. A number of researchers feel that the optimum frequency is between 200 and 300 MHz, but authorization to operate in this range is very difficult to obtain.

After each pulse is transmitted, the echo is sampled at specified times (*range gates*) that correspond to predetermined heights. If t is the time between transmission of the pulse and a range gate sample time, the corresponding range, r , is

$$r = ct/2 \quad (\text{A.9})$$

The divisor of 2 arises because t is the two-way time – that is, the time from the profiler up to the scattering volume and the back down to the profiler. A range of 15 km, for example, corresponds to $t = 100 \mu s$.

For each range gate, echoes are received from a spread of ranges, or heights, as shown in Figure 5 of Chapter 2. This spread of ranges, Δr , is called the *range resolution* and is equal to

$$\Delta r = c\tau/2 \quad (\text{A.10})$$

where τ is the pulse length in time units. (Once again, the divisor of 2 arises from the two-way travel time.) For example: a pulse length of $1.0 \mu s$ corresponds to a resolution of 150 m. The height assigned to a given resolution cell is the midpoint of that cell.

Most users want as small a resolution as possible; however, there are a number of trade-offs that must be considered. One is the amount of energy transmitted. Clearly, the shorter the pulse, the smaller the energy transmitted (other things being equal), and therefore the lower the maximum height that will yield usable echoes. Another consideration is bandwidth. Short pulses contain a wider spread of frequencies than do long pulses. The bandwidth of the frequencies transmitted is approximately equal to the reciprocal of the pulse length. Thus, a $1 \mu s$



WIND PROFILING RADARS DIFFERENT FREQUENCIES

	1 GHz	400 MHz	50 MHz
RANGE	0.2-5 km	0.2-14 km	2-20 km
ANTENNA SIZE	100 m ²	120 m ²	10,000 m ²
PEAK POWER	5 kW	40 kW	250 kW
BEAM WIDTH	2°	4°	3°
RELATIVE BANDWIDTH OF 1 μs PULSE (150 m RESOLUTION)	0.1%	0.25%	2%
EFFECT OF RAINDROPS	Large	Moderate	Small

Figure A-3 Typical properties of profilers operating at common frequencies. (The height range shown is representative, but considerable variation can occur, depending upon meteorological conditions and operating parameters.)



pulse length corresponds to a bandwidth of approximately 1 MHz. Shorter pulses require wider bandwidths still. At 50 MHz it is difficult to obtain authorization to operate with a bandwidth wider than 1 MHz. Shorter pulse lengths are also more difficult to produce electronically and even small errors become more serious. For example: at 50 MHz a $0.5 \mu s$ pulse (75 m resolution) contains only 25 cycles; the rise and fall times of the pulse each require several cycles and so an error of, say, two cycles can make a significant difference in the amount of energy transmitted. Finally, the filter in the receiver is matched to the bandwidth of the pulse transmitted; short pulses (wide bandwidths) mean that more cosmic background noise is going to be received. In general, short pulses are more appropriate and easier to generate at higher operating frequencies.

The altitude of the lowest height measured (first range gate) depends on the pulse length and the system recovery time. The pulse length is important because the receiver is disconnected from the antenna while the pulse is being transmitted. The lowest conceivable first range gate for such a system corresponds to half the resolution. For example, if the resolution is 150 m, the lowest possible first range gate is at 75 meters (that is, echoes would be received from the 0 to 150-meter range at the sample time). In practice, the first range gate is higher than this as the receiver is not reconnected to the antenna immediately after pulse transmission. The electronics has to be given time to recover after transmission of the pulse, as short-lived transients are induced in the circuits by the pulse. In practical terms, the first range gate is normally set at an interval approximately equal to the resolution.

Range aliasing occurs when echoes are received from more than one pulse at the same time. Some types of range aliasing are unavoidable in practical terms, such as echoes from meteor trails (at heights of about 80 -100 km), ionospheric echoes, and so forth. These can be largely compensated for by coding the phases of the transmitted pulses so that range-aliased echoes have pulse-to-pulse phase jumps. The effect is to make these extraneous echoes appear as extra noise in the sys-

tem, or to shift the offending echoes to a different part of the spectrum where they can be ignored (the exact effect depends upon the method). To eliminate range aliasing of echoes from within the range of interest, the *pulse repetition period* (PRP) is chosen long enough that echoes from the greatest altitude of useful data have been received before the next pulse is transmitted. This is given by

$$\text{PRP} > 2 r_{\max}/c \quad (\text{A.11})$$

where r_{\max} is the greatest expected range of useful data. For example: if $r_{\max} = 20 \text{ km}$, then $\text{PRP} > 133 \mu\text{s}$.

A.1.4 WIND VECTOR CALCULATIONS

Radial velocity measurements are made at each specified height along each beam. For each height, the radial velocities from the three beams are combined to calculate the east-west (zonal), north-south (meridional), and vertical components of the wind, u , v , and w , respectively.

If the beams are oriented to the east at zenith angle θ_1 (beam 1), to the north at zenith angle θ_2 (beam 2), and to the vertical (beam 3), the radial velocities along these three beams are

$$V_1 = u \sin \theta_1 + w \cos \theta_1 \quad (\text{A.12})$$

$$V_2 = v \sin \theta_2 + w \cos \theta_2 \quad (\text{A.13})$$

$$V_3 = w \quad (\text{A.14})$$

Normally, θ_1 and θ_2 will be the same, about 15° . From these three equations, the u , v , and w are computed, as V_1 , V_2 , and V_3 are measured and θ_1 and θ_2 are known.

If the orthogonal beams 1 and 2 are not oriented east and north, but rotated clockwise at angle ϕ (i.e., ϕ is the azimuth of beam 2), then their radial velocities are

$$V_1 = u' \sin \theta_1 + w \cos \theta_1 \quad (\text{A.15})$$

and

$$V_2 = v' \sin \theta_2 + w \cos \theta_2 \quad (\text{A.16})$$

where u' and v' are the horizontal velocities in the planes of the beams – that is, rotated ϕ to u (east) and v (north). Using the u' and v' determined this way, the u and v components are found from

$$u = u' \cos \phi + v' \sin \phi \quad (\text{A.17})$$

and

$$v = -u' \sin \phi + v' \cos \phi \quad (\text{A.18})$$

Three beam systems operate on an assumption of homogeneity in the wind field over the spatial separation of the three beams. This is usually a safe assumption. However, if there is significant wave structure in the wind field, the wind may be different in the three beams and the resulting calculations of u and v may be in error. There are ways to allow for this, including the use of five beams, but a thorough discussion of this is beyond the scope of this document.

A.2 TYPES OF RADAR SCATTERING

In wind profiling, the transmitted pulses can be scattered by two types of atmospheric targets: (1) irregularities in the index of refraction of the air and (2) hydrometeors, particularly wet ones (rain drops, melting snow, water coated ice). The received echo power, P_r , is calculated as

$$P_r = (\text{const}) \frac{P_t \tau A_e}{r^2} \eta \quad (\text{A.19})$$

where (const) is a combination of constants, both mathematical and physical (such as system efficiency), P_t is the transmitted power, and η

is the reflectivity of the scattering volume. In this section we shall explore the nature of this reflectivity for both scattering types.

A.2.1 SCATTERING FROM REFRACTIVE IRREGULARITIES

Because the radio refractive index of air, n , is so nearly equal to one, it is normally expressed in terms of N , which is defined as

$$N = (n - 1) \times 10^6 \quad (\text{A.20})$$

The quantity N is simply the variable part of n and has units that are referred to as "N units". Bean and Dutton (1966) found that N can be expressed as

$$N = \frac{77.6}{T} \left(P + \frac{4810 e}{T} \right) \quad (\text{A.21})$$

where P is the pressure of the (dry) air in millibars (mb), e is the vapor pressure in mb, and T is the temperature in kelvins. At sea level, N is typically between 250 and 400. It is the variations in N over short distances (one-half the radar wavelength) that are of particular interest.

Even though the value of N depends upon the variables P , T , and e , the *variations* in N depend primarily on variations in T and e . The variations in P are generally unimportant as they are associated with large-scale, slow-moving weather patterns or high velocity acoustic waves, neither of which give variations relevant to wind profiling. On the other hand, small scale variations in T and e are caused by turbulence and typically have lifetimes of a few seconds, long enough to scatter thousands of pulses.

The variations in n over short distances are normally expressed in terms of D , the *refractive index structure function*, as

$$D_n(l) = \langle [n(\vec{r} + \vec{l}) - n(\vec{r})]^2 \rangle \quad (\text{A.22})$$

where the angular brackets denote time average, \vec{r} is the position vector of any selected point, and \vec{l} is the displacement vector of another nearby point from the first. The difference in n is squared to assure that positive quantities always result. Atmospheric turbulence is generated at scales of tens to hundreds of meters by wind shear and convection (updrafts, downdrafts, etc.). These large eddies are thought to break up into smaller eddies, which break up into still smaller ones, and so on until the turbulence energy is dissipated at very small scales by viscous heating. The energy is thus input at the large scale sizes and dissipated at the small scale sizes. The scale sizes between these, where the turbulence energy is "just passing through", is referred to as the *inertial subrange*. The smaller scale sizes are in the *viscous subrange*. It has been shown (Tatarskii, 1971) that in the inertial subrange the dependence of D upon l can be expressed explicitly

$$D_n(l) = C_n^2 \vec{l}^{2/3} \quad (\text{A.23})$$

where C_n^2 , the "constant of proportionality", is known as the *refractive index structure parameter* or *refractive index turbulence parameter*. It does not depend upon l . Therefore, within a given sampling volume at a given time, measurements of C_n^2 at different scales should be the same, as long as the scales are within the inertial subrange. Therefore, C_n^2 is one of the standard parameters used in discussing turbulence.

In the inertial subrange, the radar reflectivity is proportional to C_n^2 and is given by

$$\eta = 0.38 C_n^2 \lambda^{-1/3} \quad (\text{A.24})$$

where λ is the radar operating wavelength. By combining equations (A.19) and (A.24) we see that a measurement of P_r can be converted into C_n^2 . The wind profiler is therefore also a C_n^2 profiler.

The height range of useful returns depends on the operating frequency and degree of turbulence. Obviously, the stronger the turbulence, the stronger the echo. In addition, viscous forces are height dependent, and the dividing line between the inertial and viscous sub-

ranges is therefore also height dependent. There are fewer small scale than large scale eddies at the greater heights and therefore the higher frequency profilers cannot "see" as high as the lower frequency profilers. (It must be pointed out, however, that most wind profilers are height-limited by their power-aperture product; as a result, few profilers are powerful enough to reach the height corresponding to the dividing line between the inertial and viscous subranges.)

A.2.2 SCATTERING FROM HYDROMETEORS

Over the years, radar meteorology has been largely a study of radar reflections from hydrometeors. See Battan (1973) and Gossard and Strauch (1983) for details. The reflectivity of hydrometeors depends upon their size distribution, density, dielectric properties, shape and orientation, and the radar's wavelength. For a single particle, the reflectivity has been shown to be

$$\eta = (\text{factors}) d^6 / \lambda^4 \quad (\text{A.25})$$

where d is the diameter of the particle and *(factors)* depends upon the dielectric constant of the particle, its shape, and its orientation. The volume being probed by the radar pulse contains large numbers of such particles of various sizes, and so equation (A.25) must be integrated over the size distribution to find the total particle reflectivity.

Note the equation's dependence on wavelength. Typical meteorological radars operate at wavelengths on the order of 5 to 10 cm, whereas wind profilers operate typically near wavelengths of 75 cm and 6 m. Therefore, hydrometeors are some 10^4 times less reflective to the wind profilers than to conventional weather radars.

It should also be noted that liquid water (rain drops, melting snow, water coated ice particles) are considerably more reflective than solid ice at radar wavelengths.

A.2.3 COMPARISON OF REFLECTIVITIES

The reflectivity of clear air varies as $\lambda^{-1/3}$, whereas that of hydrometeors varies as λ^{-4} . Weather radars are therefore very sensitive to precipitation and very insensitive to the clear air. The reverse is true for the VHF wind profilers. There is no distinct cut-off in wavelength between the two types of radar as this sensitivity depends strongly on atmospheric conditions. Observations show, however, that wind profilers operating at 400 MHz and above do detect rain, whereas those at 50 MHz detect rain only when it is heavy.

Precipitation, when detected, can be a problem in some circumstances. Clearly, if one is interested in the vertical motion of the air, precipitation is a problem, as the vertical velocity measured is that of the precipitation, and not the air. Likewise, C_n^2 cannot be determined in the presence of detected precipitation. On the other hand, if the horizontal wind is the main interest, precipitation may help, as it presents a larger target than the clear air alone. The horizontal motion of light precipitation is the same as that of the air (*i.e.*, the wind) and as long as the precipitation is the same in the three beams (which is usually the case) the horizontal wind calculations will be correct. Heavy precipitation may not follow the wind, which would make accurate wind velocity measurements impossible.

In some cases, spectra from the vertical beam will show a double peak: one corresponding to the clear air and the other to precipitation. This is the most favorable case, as both the vertical fall velocity of the precipitation and the vertical speed of the air can be measured together. This type of analysis, of course, would require special software.

If precipitation varies over the spacing of the three beams of the wind profiler, the wind calculations will be wrong. It is best to ignore such data. On the other hand, if a five beam system is used, it is possible to calculate the horizontal divergence of the wind field, something quite useful in researching storms. Again, special software is required for this.

A.3 DIGITAL SIGNAL PROCESSING

Any wave form, no matter how complex, can be thought of as the summation of a large number (perhaps an infinite number) of sine waves of different amplitudes and phases. The variation of amplitude of these sine waves as a function of frequency is called a spectrum. One objective of signal processing is to determine the spectral content of a given wave form. In the case of wind profiling, the wave form in question is the time-varying echo strength (pulse to pulse) for a given range gate. The result of the signal processing is a spectrum showing the Doppler shifted echo from which the radial velocity (and other quantities) can be computed.

A.3.1 THE DISCRETE FOURIER TRANSFORM

The transformation of a wave form from the time to the frequency domain is known as a *Fourier transformation*. In particular, if the wave form is discrete (that is, sampled at regular intervals) the process is known as the *Discrete Fourier Transform* (DFT). There are several numerical schemes or algorithms for computing the DFT. One rapid method commonly used in digital computers is known as the *Fast Fourier Transform* (FFT). This is the method often used in wind profiling. No attempt will be made in this Appendix to lay out the foundations of Fourier analysis, but some of the basic relationships relating to it will be given.

If the input to a DFT is a single discrete wave form, the output will be a frequency spectrum showing the Doppler shift, but it will not be possible to know if the Doppler shift is positive or negative. To remove this ambiguity, the echoes from each pulse transmitted are sampled twice for each range gate: one sample is taken from the direct input signal and the other is taken from the input signal that has been delayed one-quarter wavelength (90° phase difference). These signals are known as the *in-phase* and *quadrature components* (or the *sine* and *co-sine* components). It is these phase differences that determine whether a Doppler shift is positive or negative.

For each range gate, the discrete samples are spaced apart in time at the *pulse repetition period* (PRP). The inverse of this is the *pulse repetition frequency* (PRF), the rate at which the samples are taken. The resulting discrete waveform (for each height) is the sum of many sine curves of various amplitudes and frequencies. In order to be able to determine any one of these sine curves, it must be sampled at least twice per wavelength. Thus, the highest possible Doppler frequency that can be detected is half the PRF. As discussed in the following section, several consecutive samples are normally averaged together before the FFT is calculated. Thus, the effective sampling rate is lower. If *NCOH* is the number of samples averaged, then the maximum frequency detectable is

$$f_N = \frac{\text{PRF}}{2 (\text{NCOH})} = \frac{1}{2 (\text{NCOH}) (\text{PRP})} \quad (\text{A.26})$$

This maximum frequency is sometimes called the *Nyquist frequency*. If the incoming signal actually had a more rapid variation than this frequency, this effective sampling rate would not detect it properly: that is, the frequency would appear lower than it really is. This is referred to as *frequency aliasing* (or, *velocity aliasing*, if the frequencies have been converted to radial velocities). This condition is effectively illustrated in movies depicting rotating, spoked wheels in which the wheel sometimes appears to rotate backward: in this case, the frame rate of the film is not fast enough to capture the true motion of the wheel, and the visual sequence of adjacent spokes overrides the true movement of individual spokes.

A fixed number (*NFFT*) of these averaged values – actually pairs of values, as both the in-phase and quadrature components must be averaged separately – are then used as input to the FFT. This number should be large enough to allow the spectrum to be defined adequately but small enough to keep the number of computations manageable for the computer that is to be used. *NFFT* is usually 2^n , where *n* is an integer, as this greatly speeds the computations. Tycho profilers use *NFFT* = 256. The output of the FFT computation is a pair of number

sets (called the real and imaginary components), each having NFFT points. These are then squared and summed point for point to yield the power spectrum, which also has NFFT points. Figure 8 in Chapter 2 shows an example of a power spectrum.

The total time required to gather the data for the FFT calculation is thus (NFFT)(NCOH)(PRP). The inverse of this is the frequency resolution of the power spectrum, Δf :

$$\Delta f = \frac{1}{(\text{NFFT})(\text{NCOH})(\text{PRP})} \quad (\text{A.27})$$

Equations (A.26) and (A.27) can be converted to their equivalents in velocity using the Doppler frequency - velocity relation ($f = -2 V/\lambda$) to get the maximum unaliased velocity:

$$V_{\max} = \frac{\lambda}{4 (\text{NCOH})(\text{PRP})} \quad (\text{A.28})$$

and the velocity resolution in the spectrum

$$\Delta V = \frac{\lambda}{2 (\text{NFFT})(\text{NCOH})(\text{PRP})} \quad (\text{A.29})$$

The negative sign is not used in (A.28) and (A.29) as V_{\max} and ΔV refer to limits, which can be positive or negative, rather than a measured velocity.

To illustrate the order of magnitude of these values, consider a 400 MHz (75 cm) profiler using NCOH = 50, NFFT = 256, and PRP = 125 μ s. This yields

$$f_N = \frac{1}{(2)(50)(125 \times 10^{-6})} = 80 \text{ Hz}$$

$$V_{\max} = (80)(0.75)/2 = 30 \text{ m/s}$$

$$\Delta f = \frac{1}{(50)(256)(125 \times 10^{-6})} = 0.625 \text{ Hz}$$

$$\Delta V = (0.625)(0.75)/2 = 0.23 \text{ m/s}$$

The choices of NCOH and NFFT are based in part on the expected V_{\max} and the desired ΔV . Note that for a different operating frequency, different values of NCOH and perhaps NFFT should be used.

A.3.2 AVERAGING

The averaging of several consecutive samples for each value used in the FFT is called *time-domain averaging* or *coherent averaging*. This process has several effects. First, it reduces the total noise power by removing the high frequency components from the signal. Removing these components has the possible disadvantage of introducing velocity aliasing, but with the proper choice of NCOH this condition can be avoided. The principal advantage of coherent averaging is the substantial reduction in the number of computations required to produce a spectrum. If no coherent averaging were done, but the same spectral resolution were required, the value of NFFT would be NCOH times larger, and the number of calculations required for the FFT would increase by the factor $(\text{NCOH})[\ln(\text{NCOH})(\text{NFFT})]/[\ln(\text{NFFT})]$. If $\text{NCOH} = 50$ and $\text{NFFT} = 256$, this increase would be a factor of 85, which is substantial.

The other type of averaging used in wind profiling is the averaging of consecutive power spectra, point for point, in the frequency domain. This is referred to as *spectral averaging* or *incoherent averaging*. This improves the detectability of the spectral peak by smoothing out the noise "floor" and making the peak better defined. The maximum height of useful data is thereby increased. The disadvantage of incoherent averaging is the loss of time resolution. For many applications this is no problem since one wind profile every few minutes is adequate. Without spectral averaging it is possible to get a profile every few seconds. The total integration time in one mode is thus

$$\text{integration time} = (\text{NCOH})(\text{NFFT})(\text{NINCOH})(\text{PRP}) \quad (\text{A.30})$$



where *NINCOH* is the number of spectra averaged together.

In the operation of a wind profiler it is common to operate in more than one mode. For the altitude range close to ground level, short pulses (yielding good height resolution) are used, and longer pulses (though producing poorer resolution) are used to reach to higher altitudes. The total dwell time for one beam is then the sum of the integration times of the modes used. It is common to integrate for about one minute per mode, so that the dwell time per beam is about two minutes. For a three beam system, the time to acquire the data for a complete wind profile is thus about six minutes; for a five beam system it would about 10 minutes. Figure A-4 is a summary of the times typically required for all the processing steps. (The numbers shown are for Tycho's Model 400 wind profiler, vertical beam, high mode.)

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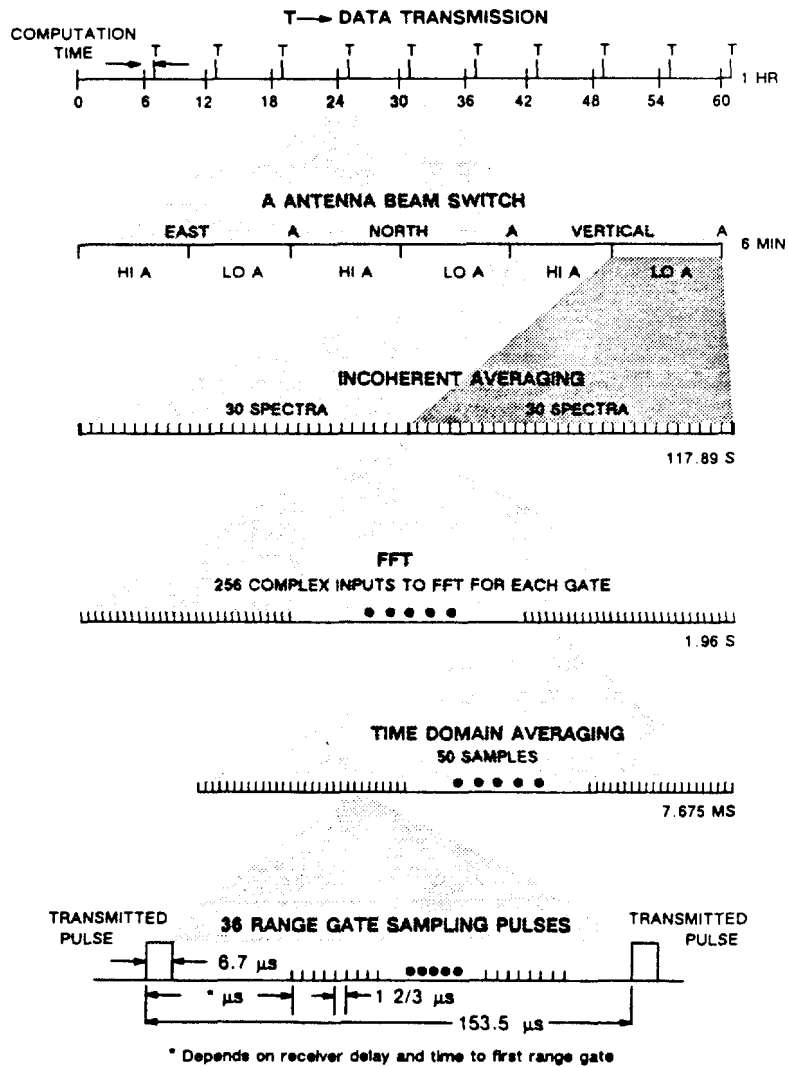


Figure A-4 Summary of timing requirements for the various processing steps. This example is for Tycho's Model 400 wind profiler vertical beam in high mode.



APPENDIX B – APPLICATIONS

The application areas for Tycho's wind profilers span many disciplines, with users ranging from government agencies to private enterprise.

B.1 METEOROLOGICAL APPLICATIONS

Weather forecasting has improved steadily over the years, but further advances depend upon the availability of significantly more weather data. Data are required at greater resolution in both time and space. This is particularly true for upper-air data, which are largely limited to twice daily balloon soundings and to satellite observations of clouds and temperatures. The wind profiler offers a means of greatly expanding our data base and thus improving forecasts for both synoptic scale and mesoscale phenomena.

B.1.1 SYNOPTIC SCALE

Weather systems exist on many scales, from global to local. The largest are the synoptic-scale systems, which extend from a few hundred to several thousand kilometers in size and have lifetimes from several days to a few weeks. These systems include planetary waves, jet streams, extratropical cyclones, and the major weather fronts. Week-to-week changes in weather are normally attributed to synoptic-scale weather systems.

The existing network of balloon-based, upper-air stations in the northern hemisphere has provided enough data to reasonably define synoptic-scale weather events. In the southern hemisphere synoptic-scale weather systems are not as well defined. Upper-air data with a greater resolution in time and space would greatly facilitate both manual and numerical forecasting. Because the Tycho's wind profiler radar is completely automatic, it can operate at unmanned, remote sites. As it is so economical to operate, it is ideal for filling in the gaps in the synoptic network and replacing the wind-only (PILOT) balloon observations made at certain upper-air stations.

B.1.2 MESOSCALE

The mesoscale encompasses systems that extend from a few kilometers to several hundred kilometers in size and have lifetimes from several minutes to a few days. Most significant weather is associated with mesoscale phenomena: thunderstorms, tornadoes, and tropical cyclones are all examples of mesoscale weather systems.

If a mesoscale convective system remains stationary, devastating floods can occur. If it moves steadily, beneficial precipitation often results. It is critical, therefore, to be able to forecast the movements of these systems accurately. Because existing upper-air sounding stations are spaced hundreds of kilometers apart and gather data only once every twelve hours, mesoscale systems are often missed. As a result forecasts are often inaccurate. Improvements in weather forecasts clearly depend upon observations being made more frequently and with a closer spacing. The Tycho wind profilers offer significant advantages over an extensive balloon launching program because they measure wind profiles much more economically and accurately than the common radiosonde. For mesoscale research purposes, high resolution Vaisala radiosondes are available for thermodynamic measurements.

B.1.3 COMMERCIAL WEATHER SERVICES

Weather reports and forecasts provided by the government are general, as they must serve a wide spectrum of users. In the USA, specialized forecasts for specific needs are normally left to the private sector. Some industries, such as aviation and television, employ their own in-house staff to provide these services. Other industries don't find this practical, so they turn to commercial weather services companies. One industry needing specialized forecasts is agriculture, where the most important factors are precipitation and temperature. Detailed knowledge of the wind is needed to forecast these factors accurately. In forest management it is important to be able to predict the motions of forest fires. The need for wind information is critical. In these areas and many others, the wind profiler can play an important role.

B.2 AVIATION AND AEROSPACE APPLICATIONS

B.2.1 IMPROVED FLIGHT PLANS

The aviation industry stands to reap substantial benefits from the wind profiler. One important area will be flight planning. Today, a commercial aircraft must carry enough fuel to be able to stay aloft for a period substantially longer than the time required to simply fly to its destination. Extra fuel is required to make unexpected deviations around storms or remain "stacked" above an airport while other planes, also delayed by weather, are landing. With a reasonably dense network of wind profilers in place providing continuous data, pilots will be able to file more accurate flight plans. The amount of fuel required for a flight will thus be reduced. It has been estimated (Carlson and Sundararaman, 1982) that the commercial aviation industry could save \$100 to 300 million per year in fuel, in the United States alone, through flight planning that used a network of wind profilers.

B.2.2 FLIGHT SAFETY

Another benefit is increased flight safety and comfort for crew and passengers. The wind profiler not only measures the wind, it also measures the degree of atmospheric turbulence. With this information, pilots could plan flights not only to maximize fuel efficiency but also to avoid regions of enhanced turbulence. The avoidance of mild turbulence will reduce air sickness, spilled coffee, and other similar annoyances. The avoidance of severe turbulence will reduce accidents and save lives.

One of the most serious weather problems in aviation is that of strong wind shear and microbursts, especially in the vicinity of airports. Wind shear was a factor in some 40% of the fatalities in U.S. commercial passenger traffic over the last 21 years. Although the wind profiler is not well suited for detecting microbursts (the microburst would have to be very near the site), it has the potential of detecting the conditions

that occur before the onset of microbursts. Locating wind profilers at or near airports will facilitate this application.

Take-off and landing operations on aircraft carriers and other ships is greatly influenced by winds. A low level, high resolution version of the system, in which the motion of the ship is allowed for, is under development. It will be of great utility in these applications. Wind profilers on ships will also be of direct use in tactical weather intelligence and weather forecasting.

Petroleum companies can use the wind profiler as helicopters are an important mode of transportation to and from oil rigs in the ocean. Wind information is very important for take-off and landing. Measurements should be made as close to the rig as possible. The antenna for the radar could be embedded into the landing pads on oil rigs and thus wind information would be obtained at the rig itself. Tycho's low level, high resolution version of the system is well suited for such applications.

Additional synoptic and sub-synoptic data improve the weather services that are critical for off-shore operations. More accurate and more frequently updated forecasts of winds and sea state can be made.

B.2.3 SPACE AGENCIES

A detailed knowledge of the vertical structure of the wind is needed for launching missiles and satellites. Both the accuracy of the launch and the mechanical stresses on structural members of the rocket are affected by the wind. For this application a "super" wind profiler that measures to great altitudes should be located as close to the launch pad as is practical. In the case of the Space Shuttle, there is no second chance for a landing. A small wind profiler at the landing site would provide an extra margin of safety.

B.3 ENVIRONMENTAL APPLICATIONS

The trajectories and dispersion of air-borne pollutants are largely controlled by the wind and air turbulence. There is a wide variety of

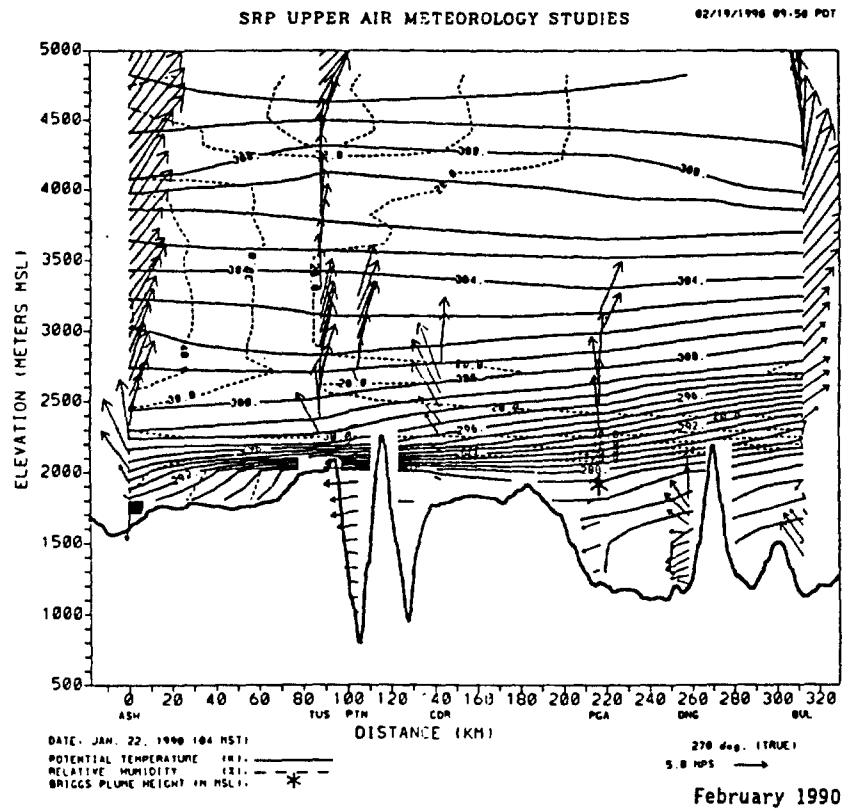


Figure 4 Same as Figure 3 for 0400 MST on January 22, 1990.

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sources for air-borne pollutants – power plants (both fossil fuel burning and nuclear), chemical factories, forest fires, automobile exhaust, and many others. In time of war, potentially very serious pollutants are Nuclear/Biological/Chemical (NBC) agents used in battles.

Tycho's wind profilers would be extremely useful in these situations. They are needed for basic research studies on the dispersion and transport of pollutants, such as acid rain studies. They would be crucially important in emergency situations, such as the accidental release of radioactive particles from a nuclear power plant or in NBC warfare. With a knowledge of the trajectories and diffusion rates of such noxious materials, defense forces could take evasive or protective action. Similarly, civilian populations could be taken to safety and unnecessary evacuations could be avoided.

B.4 ACADEMIC APPLICATIONS

Wind profilers will undoubtedly find many applications in the academic community, not only in universities and colleges but in research institutes and government laboratories as well. These applications fall into the broad categories of research and education.

B.4.1 RESEARCH

Mesoscale phenomena are still poorly understood. Measurements of many kinds, including winds, are needed. Some of the areas needing study are: the lifetimes of mesoscale convective systems (MCS) – how they form and dissipate; the interactions of MCSs with other weather systems, both on a larger and smaller scale; and the motions of these systems – why some move steadily while others remain relatively motionless. Wind profilers can play a significant role in this research and, indeed, are already starting to do so.

Atmospheric turbulence and eddy diffusion studies can be aided by wind profilers. The radar echo power and width of the spectral peak are both a measure of the degree of turbulence. Thermal and particle diffusion rates are, in turn, related to the degree of turbulence. These



studies are still in their infancy and we can expect to see substantial progress in the years to come.

B.4.2 TRAINING AND EDUCATION

As wind profilers become more common, there will be a growing need to train students in the interpretation of their data. This includes not only the meteorological implications of the winds measured but also the detailed analysis of the Doppler spectra.

Once a network of wind profilers is in place and mesoscale weather systems become better understood, weather forecasting will improve. Initially, relatively few people will know how to use the new data for weather forecasting. It will be important to educate forecasters at local weather service offices to better understand local atmospheric effects in light of this newly available data.

APPENDIX C - COMPARISONS OF GROUND-BASED UPPER-AIR WINDFINDING SYSTEMS

Operational upper-air windfinding systems fall into two basic categories; balloon tracking systems and remote-sensing systems. They differ from each other in the source of the primary information. No one system is superior in every regard. The trade-offs are mainly between mobility and desired measurement capability.

In addition to performance characteristics, there are three important concepts to consider when comparing the windfinding systems. These are electromagnetic activity, dependence on remote transmitters, and position fix.

- Systems radiating electromagnetic energy in order to perform the measurement are called "active." The others are called "passive."
- Systems needing signals from some remote source - for example transmitters of radionavigational networks - are called "dependent." The others are called "independent."
- Systems that make it possible to fix the profile at the observation site are considered to have a proper position fix, whereas the others, which use free flying balloons, have an improper position fix.

In this Appendix, we consider only operational systems. Other wind profiling methods, such as tracking radar chaff or smoke trails and the Spaced Antenna Drift (SAD) technique, are interesting research areas, but they cannot be considered operational.

C.1 NAVAID-BASED SYSTEMS

There are two navigational aid (navaid) frequency bands that are used for windfinding purposes. One is the VLF band between 10 and 15 kHz. It uses a network of eight Omega transmitters, each operating at several frequencies (the most widely used being 13.6 kHz). The other operates at 100 kHz and uses the Loran-C system.



In the navaid-based systems, the signals from the navaid network in question are received by the radiosonde and then relayed to the ground station. In the Omega systems, the primary information is the phase difference between the received remote signal and a locally generated reference signal. In the Loran-C systems, the basic information is the propagation time delay between network's master and slave stations. In both systems at least three independent time delays or phase differences are required but good performance usually requires an overdetermined solution (more stations) to compensate for poor signal-to-noise-ratio and other sources of error.

C.1.1 OMEGA-BASED SYSTEMS

Systems based on the Omega networks are an accurate and reliable means for windfinding, if the use of the radiosonde is justified. In many comparisons the accuracy has been proven satisfactory and reliability has been very good. The main advantages are:

- + easy to use
- + reliable
- + satisfactory accuracy
- + accuracy is not range dependent
- + high degree of automation
- + good portability
- + good maintainability
- + passiveness
- + excellent for airborne and shipborne use and soundings made from a moving vehicle
- + good electromagnetic compatibility

The disadvantages are:

- accuracy depends on time of the day and time of the year
- sensitive to charged raindrops
- profiles are too smooth
- lowest applicable level is 600 m
- expensive radiosonde

- dependent on remote transmitters
- improper position fix

C.1.2 LORAN-C BASED SYSTEMS

The accuracy of the systems based on the Loran-C network is excellent in those areas where Loran-C signals are available. The required processor capacity to achieve good quality results is much greater than in the Omega-based systems but it can easily be achieved by today's technology. The Loran-C systems require the use of a radiosonde, so in this respect is expensive. The advantages of the Loran-C based systems are essentially the same as those of Omega-based systems:

- + high accuracy in certain areas
- + lowest level 100 m
- + good vertical resolution
- + accuracy is not range dependent
- + easy to use
- + reliable
- + high degree of automation
- + good portability
- + good maintainability
- + passiveness
- + suitable for airborne and shipborne use and soundings made from a moving vehicle
- + good electromagnetic compatibility

The disadvantages are few and can be avoided if the area of operation is suitable. In many cases, if Loran-C signals are not available the same system can make use of Omega signals with minor changes.

- performance depends on weather conditions
- dependent on remote transmitters
- expensive radiosonde
- improper position fix